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Precision in Machining: Research Challenges

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May 1995



U.S. DEPARTMENT OF COMMERCE
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Executive Summary

This report looks at critical research needs for leading-edge technology developments in machining and precision that are important to the competitiveness and economic growth of the U.S. discrete-part industry. This industry produces individual products such as aircraft, automobiles, industrial machinery, home appliances, electric equipment, and all the individual components of which they are made. The discrete-part industry is an important segment of the U.S. economy. In 1991 the value of shipments of durable goods produced by its key sectors amounted to over \$1089 billion (10^9), or about 19 % of the GDP.

The findings of the report are based upon analyses of published data and a workshop on precision in machining sponsored by the National Institute of Standards and Technology in which representatives from industry, the National Laboratories, and academia participated.

Traditional machining methods (e.g., turning, milling and grinding) have changed gradually over time. Most improvements have been evolutionary. However, with the advent of numerical controllers and Computer Numerically Controlled (CNC) machines there has been an accelerated trend towards higher speed, greater flexibility, increased automation, more complex part geometries, and greater precision. Advances in machine tool configurations are enabling the machining of more complex geometries in one setup, thereby increasing throughput, agility, and accuracy. The increased use of advanced materials is spurring the growth of emerging processes. The accelerated pace in the introduction of new products and models is resulting in a search for greater manufacturing flexibility. Flexibility and rapid changeover, through the use of modular tooling and fixturing, is becoming increasingly important. The search for flexibility is also resulting in a shift from dedicated machinery to increased use of multi-purpose CNC machining centers. Increased *flexibility*, increased *precision*, increased *automation*, increased use of *advanced materials*, and the emergence of *new processes* are the key driving forces in manufacturing today.

To remain competitive in world markets, the discrete-part industry must produce innovative, quality products at competitive costs in a timely manner. As evidenced by the success of Japan, improvements in, and control of, manufacturing precision are critical to meet market demands. Tighter tolerances are required for interchangeability, automatic assembly, miniaturization, integration, design simplicity and improved performance and reliability. Improvements in machining precision require better understanding of machining processes, more accurate machine tools and robust adaptive process control using deterministic manufacturing principles, in-process, process-intermittent and post-process measurements. Technology and manufacturing leaders see in-process measurement and control as the key technology for machining competitiveness.

Both improvements in, and control of, manufacturing precision are dependent upon the availability of a supportive infrastructure which includes measurement, modeling and analyses methods, factory-hardened sensors, standards, reliable machining data and databases on the cost of precision. The importance of metrology to manufacturing precision cannot be underestimated. Accurate measurements are required for process control, to insure product quality, and to improve manufacturing precision. In the area of machine tool characterization, there is an urgent need to develop fast, in-situ, practical measurement procedures and meaningful accuracy parameters. Special efforts are needed to harmonize the terminology,

and the measurement and analysis methods embodied in national and international standards. Special efforts should be made also to develop the interface standards for controllers and sensors used in process measurement and control. Because of its third party objectivity, NIST is in a unique position to provide the sustained and continuous leadership required in this area.

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1. Introduction

This report looks at critical research requirements[†] for leading-edge technology developments in precision machining that are important to the competitiveness and economic growth of the U.S. discrete-part industry. It identifies the metrological and technical challenges these requirements pose to the Automated Production Technology Division (APTD) of the Manufacturing Engineering Laboratory (MEL) of the National Institute of Standards and Technology (NIST). The findings reported in this report will be used to establish APTD long-term research priorities to ensure that NIST provides industry with the sustained infrastructural support it needs to successfully compete in both national and international markets.

This report is based on analyses of published data, and the findings of a workshop on precision machining sponsored by APTD, held on October 12 1994, in which representatives from industry, the National Laboratories and academia participated. A list of workshop participants is presented in Appendix A.

The analyses contained in this report are organized into five areas: machine tool accuracy characterization and specification, machine tool accuracy enhancement, closed-loop precision manufacturing, process modeling, and emerging machining processes.

1.1 The Discrete-Part Industry

Precision machining, the ability to repeatedly manufacture parts to specified tolerances by removing material in the form of chips or swarf, is of vital importance to the discrete-part industry. This industry produces individual products such as aircraft, automobiles, industrial machinery, home appliances, electrical machinery, instruments and related products, and all the individual parts of which they are made. The American discrete-part industry is large¹. As indicated in Table 1, in 1991 the value of shipments of durable goods produced by its key sectors amounted to over \$1089 billion (10^9), or about 19 % of the GDP². For this industry to remain competitive in the global market, the ability to introduce quality products in a timely manner at the right cost is of vital importance. As evidenced by the success of Japan, these are key factors in achieving dominance of world markets.

In 1991, manufacturing operations accounted for 18 % of the U.S. GDP, or about \$ 1,026 billion. Discrete-part fabrication represents about 30 % of manufacturing operations, with 40 % to 50 % dedicated to assembly processes, and the balance to miscellaneous manufacturing tasks such as packaging, servicing, and maintenance³. About half of discrete-part manufacturing operations are made up of machining operations, the other half is made up of other processes such as forming, stamping, and casting. Accordingly, machining in the U.S. amounts to an annual figure of approximately \$154 billion. Of this, 75 % can be attributed to four main machining processes: turning, milling, drilling, and grinding.

[†] Research requirements are identified irrespective of the organization where the research is to be carried out.

Table 1

**Value of Shipments of Key Sectors of the U.S. Discrete-Part
Manufacturing Industry for 1991^{2,4}**

<i>Discrete-Part Industry Sector</i>	<i>SIC Code</i>	<i>Shipments (Billion \$)</i>	<i>Value Added (Billion \$)</i>
Fabricated Metal Products	34	157	77
Industrial Machinery and Equipment	35	243	124
Machine Tools (cutting type)	3541	(2.1)	
Machine Tools (forming type)	3542	(1.0)	
Special Dies, Tools, Jigs and Fixtures	3544	(8.9)	(6.3)
Machine Tool Accessories	3545	(4.5)	(3.0)
Electronics: Other Electric Equipment	36	198	107
Transportation Equipment	37	364	152
Motor Vehicles and Equipment	371	(206)	(73)
Aircraft and Parts	372	(102)	(49)
Instruments and Related Products.	38	127	82
Measuring and Controlling Devices	382	(32)	(20)

1.2 The Machine Tool Industry

Machine tools are the main tools used to manufacture discrete products, their components, and the machines or tools used to make them. Machine tools used for machining operations are listed in Table 2. The principle users of these machines are job shops, the aerospace industry, the defense industry, producers of motor vehicles and related products, producers of construction and agricultural machinery, the home appliances industry, and the makers of industrial and electrical machinery. Improvements in machine tool technology can have dramatic effects on overall manufacturing performance. The machine tool industry is of vital importance to both the manufacturing industry and the national security, even though the U.S. annual machine tool consumption amounts to only \$4.2 billion.

The discrete-part industry represents an important segment of the U.S. economy. To remain competitive in world markets, this industry must focus on producing the quality products that customers want, at competitive costs, and in a timely manner. On the manufacturing side, industry is dependent on the ability of the machine tool industry to provide the required innovations in machining processes and equipment. Without a healthy domestic machine tool industry, U.S. manufacturers are dependent on foreign suppliers. These often do not provide U.S. industry with access to the latest technology. As stated in the RAND report "this need not result from any conspiracy to deny the United States access to these tools but rather because machine tool makers worldwide tend to first sell their most current product lines close to home to ensure that any problems are easily fixed⁵." However, as a 1990 General Motors study on machine tools noted, typically there is a lag of one to two years in the application of the latest foreign machine tool technology to machines sold in the U.S.: "If you buy the very best from

Table 2

Inventory of U.S. Machine Tools in 1989⁶

	<i>Installed Units</i>	<i>% NC</i>	<i>Age of Machines</i>	
			<i>% 0-4 Yrs</i>	<i>% 5-9 Yrs</i>
Grinding Machines	435000	3	15	25
Turning Machines	404000	18	15	19
Drilling Machines	285000	4	12	22
Milling Machines	249000	11	15	26
Cutoff & Sawing Machines	205000		20	30
Machining Centers	54000	100	44	36
Honing, Lapping & Polishing Machines	49000		11	28
Boring Machines	48000	22	12	20
Tapping Machines	32000		13	32
Gear Cutting & Finishing Machines	30000	3	5	7
Electrical Machining Units	19000		31	33
Broaching Machines	17000		11	16
Station-Type Metalcutting Machines	13000		14	30
Laser & Thermal Cutting Machines	10600	42	50	25
Threading Machines (not mill, grind, roll)	9600		13	15
Waterjet Machines	1300		14	16
Miscellaneous	10700	19	8	24

Japan, it has already been in Toyota Motors for two years, and if you buy from West Germany, it has been with BMW for a year and a half⁵."

Close proximity between the makers of machine tools and their users can facilitate process innovations that raise productivity and sustain industrial competitiveness. It accelerates the development of new tools tailored to specific customer needs, and their introduction on the shop floor. For example, the successful alliance between the makers of machine tools used for processing plastic, the respective die and mold makers, plastic bottle producers, and soft-drink bottlers has enabled the U.S. to remain a world leader in each of these areas⁷.

Entering the 1980s, the U.S. machine tool industry enjoyed a long-held leadership position. However, the U.S. share of world markets dropped from 20 % in 1980 to just over 7 % a decade later, effectively reducing its position to that of a second-tier producer, as can be seen Figure 1. This decline was precipitated by five factors: aggressive international competition, especially from Japan and Germany; an over-dependence on a declining and highly cyclic domestic market; the inability to combine new product technology with major manufacturing process innovations; long delivery times; and the high value of the U.S. dollar during the 1980s⁷. This loss is most evident in the domestic market where, according to the RAND⁷ study, imports surged from 24 % to 54 % of total U.S. sales in a mere decade.

The Association for Manufacturing Technology (AMT) estimated that the annual U.S. machine tool consumption in 1991 was about \$4.2 billion⁴. About 74 % of this figure represents machine tools used for machining, of which only 52 %, or \$1.6 billion, were produced in the

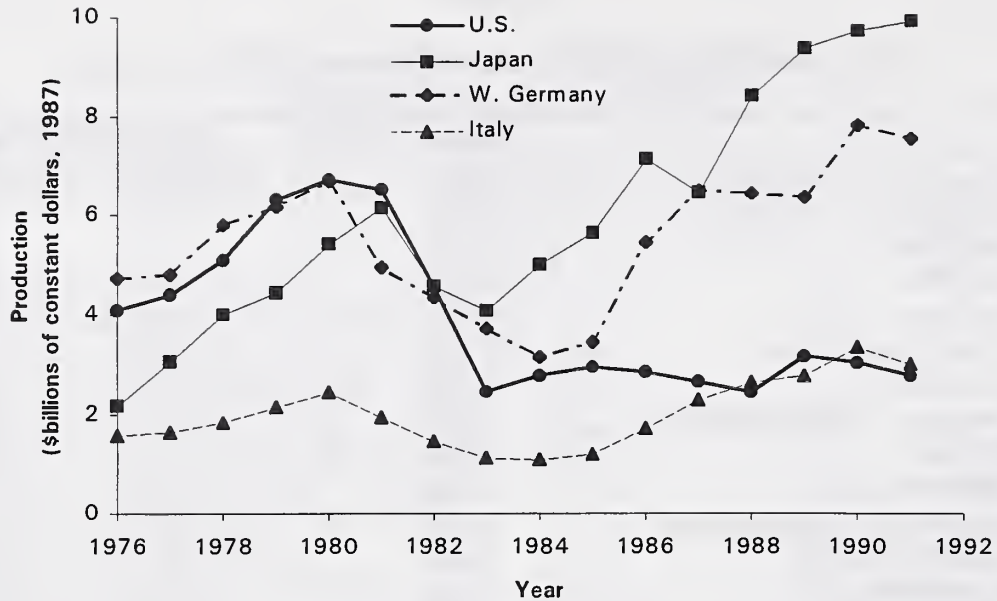


Figure 1. Machine Tool Production of Various Countries⁷.

U.S.. With the exception of a few U.S. companies with high end-products (e.g., Cincinnati Milacron in machining centers and Hardinge Brothers in turning centers) Japanese imports have virtually eliminated the U.S. production of standardized machine tools. Moreover, there is no remaining U.S. builder of large multi axis die and mold machining centers, a segment dominated by European manufacturers.

1.3 Machining

Machining is defined as the realization of a geometric feature on a discrete part by removing material in the form of chips or swarf. Typical examples range from traditional processes such as turning, milling and grinding to the nontraditional Electro-Discharge Machining (EDM), Electro-Chemical Machining (ECM) and hydrodynamic (waterjet) machining.

Machining processes can be divided into three main categories, shown in the shaded areas of Figure 2. These include (1) cutting processes, involving single- or multi-point cutting tools, each with a clearly defined or critical geometry; (2) abrasive processes, involving bonded or loose abrasives whose cutting edges have a non-critical geometry and are of random shape, and (3) nontraditional machining processes, utilizing electrical, chemical, optical, and hydrodynamic sources of energy to remove material. Nontraditional machining processes are not analyzed in this report as they will be the topic of a future workshop and report.

Machining processes are used when higher dimensional accuracy and higher quality surface finish are required than obtainable from casting, forming, or shaping processes alone. Moreover, the flexible nature of machining processes enables the cost-effective, fast manufacture of products in small batch sizes.

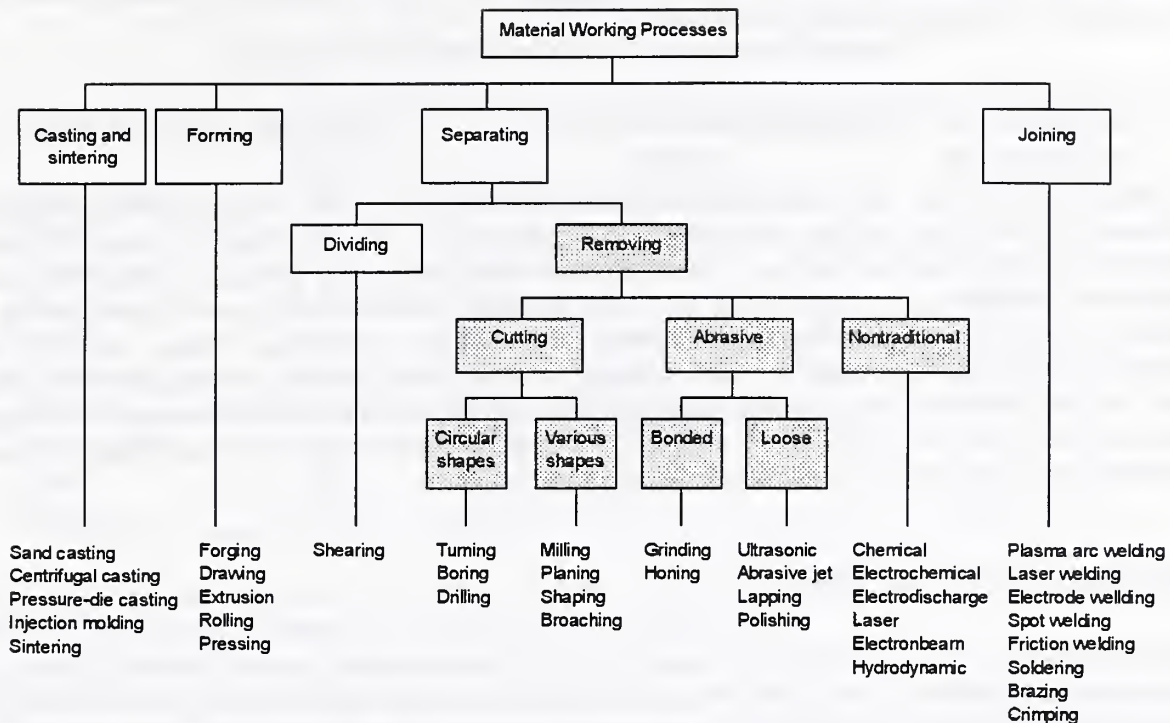


Figure 2. Classification of Processes Used to Manufacture Discrete Parts (adapted from Kalpakjian⁸ and DIN 69651⁹). The shaded areas represent machining processes.

1.4 Precision

How and how well the machined part can ultimately function or be assembled are to a large extent determined by the material properties and the accuracy of the realized geometry. The latter is determined by the precision of the machining process, defined as the ability to repeatedly manufacture parts to specific tolerances. Formally defined by ANSI Standard Y14.5 on "Dimensioning and Tolerancing," a tolerance is a number given in an engineering drawing that specifies the total amount by which a dimension is permitted to vary between the dimension of a *manufactured* part and the dimension of the part *as designed*¹⁰. Dimensional tolerances are specified for size (e.g., length), form (e.g., roundness), surface finish (e.g., roughness), and relative location of the part features (e.g., squareness). Also of interest is the integrity of the machined surface which affects part properties such as fatigue life and corrosion resistance. Factors influencing surface integrity are the temperatures generated during processing, the residual stresses, metallurgical (phase) transformations, and surface plastic deformation, tearing, and cracking.

Because machined parts are used to manufacture other parts, the relation between quality and machining precision extends beyond the products made by machining processes. For example, the quality of products made by injection molding is highly affected by the geometric

tolerances and surface quality of the molds. The critical features of these molds are manufactured using machining processes.

1.5 Precision and Competitiveness

As evidenced by the Japanese success, tighter tolerances and improved manufacturing processes and equipment are critical to meet the demand for high-quality products, quick delivery time and cost reduction. Tight tolerances on some key product components can significantly improve the overall quality of a product and simplify its design and manufacture. In addition, precision manufacturing can reduce inspection activities, scrap, rework, and assembly efforts, thereby reducing the cost and time required to bring products to the market place. In fact, improvement in precision manufacturing is vital to the implementation of design and manufacturing strategies such as interchangeability, integration, miniaturization, flexible manufacturing, automation, and zero-defects manufacturing.

1.6 Precision and Metrology

Improvements in precision machining require a better understanding of the machining process, more accurate machine tools, and robust adaptive process control based on in- and post-process measurements. Metrology plays a key role in all these processes. Advanced metrology is required to determine, model and compensate for the errors associated with the complex multi axis machine tools used in modern manufacturing. Measurement procedures and adequate sensors are required to perform fast, non intrusive, factory-hardened error assessment and machine-condition monitoring. Real-time information is required to monitor the precision of manufactured parts with minimal post-process inspection, to enable predictive maintenance, to allow error compensation, and to modify manufacturing parameters (e.g., to prevent chatter). Recent studies show that technology and manufacturing leaders see in-process measurement and control as the key technology for machining competitiveness⁷. The development of appropriate measurement methods, sensors and interface standards are key factors to the success of this strategy. Because of its leadership role in metrology and standardization, NIST can play a key role in ensuring that infrastructural developments occur in a timely manner.

1.7 Precision and Cost

In general, component features with tighter tolerances are more difficult to machine, and therefore, more expensive to produce¹¹. The approximate costs of various machined surface finishes relative to rough turning are listed in Table 3. Observations of this kind have led to the belief that there exists a nearly exponential relationship between cost and precision, even when new equipment is not needed. However, greater precision does not have to imply necessarily higher cost when the total manufacturing enterprise, including the final product, is examined. Bryan, one of the premier advocates of higher precision in manufacturing, identified 19 areas in which closer tolerances result in significant economic benefits¹³. He reports an example in which a tighter tolerance between the piston and the cylinder bore in a model

Table 3
Approximate Costs of Various Surface Finishes¹²

<i>Surface Class</i>	<i>Roughness, Ra μm</i>	<i>Typical Method of Producing Finish</i>	<i>Approximate Relative Cost</i>
Super Finish	0.1	Ground, microhoned, lapped	20
Polish	0.2	Ground, honed, lapped	17.5
Ground	0.4	Ground, lapped	12.5
Smooth	0.8	Ground, milled	9
Fine	1.6	Milled, ground, reamed, broached	6.5
Semifine	3.2	Ground, broached, milled, turned	4.5
Medium	6.3	Shaped, milled, turned	3
Semirough	12.5	Milled, turned	2
Rough	25.0	Turned	1
Cleanup	50.0	Turned	0.5

airplane engine allowed the elimination of piston rings, a simplified design, lower assembly cost, a better engine efficiency, and lower overall engine cost¹³.

The benefits of higher precision can be separated into (1) the benefits of tighter tolerances for product quality, (2) the benefits of tighter tolerances for manufacturing, and (3) the benefits of increased precision of manufacturing processes. The benefits to be derived from improved precision are tabulated in Table 4. To achieve a desired result, tight tolerances are required only for certain critical features of a given component. Thus, identification of which part features need to be manufactured to tighter tolerances is key to optimizing the design and to reducing manufacturing cost.

Comprehensive data on the relationship between precision and cost are scarce because often other factors such as design, inspection method, manufacturing process, or assembly procedures are changed at the same time as tolerance is changed¹¹. Therefore, it is difficult to determine which change resulted in what cost(s) and what benefit(s). Also, the specific tradeoff between precision and cost depends on many factors, for example, the component features, the geometry, the material, the nature of the high precision tolerances, the machine tool(s) used, the required setup(s), the accuracy of the measuring devices used to perform inspections, the practices common in an industry or a company, the number of parts to be produced, the cost of the part and the reject, the required product reliability, and many other factors. Because of the complex interdependency among all these factors, in practice, tolerance allocation is often based on judgment, primarily determined by prior experiences with similar parts, field failures, and machine availability rather than on a system approach analysis¹¹.

Recently, the Manufacturing Center at General Motors Technical Center conducted a tolerance optimization allocation analysis to reduce quality variation in realized components at minimum cost¹⁵. The tolerances of 50 features that affect the compression ratio of engine cylinders were optimized. Manufacturing cost was reduced by tightening tolerances of critical components and relaxing non-critical tolerances. The optimized design showed a 50% reduction in compression ratio tolerance resulting in a realized 0.8% increase in fuel savings

Table 4

Benefits and Costs of Improved Precision^{11, 13-20}

Benefits of Improved Precision:

• **Effects of tighter tolerances on product quality:**

- Lower operating costs
- Better product performance (e.g., longer life, higher loads, higher efficiency, better appearance and consumer appeal)
- Greater reliability and lower maintenance costs
- Safer use
- Easier repair (e.g., improved interchangeability of parts, fewer parts)
- More predictable variation in performance from part to part
- Less noise and wear (e.g., bearings, gears)
- Miniaturization

• **Effects of tighter tolerances on manufacturing:**

- Lower assembly costs (e.g., less selective assembly, eliminate 'fitting', fewer parts used, automated assembly)
- Better interchangeability allows fabrication of parts by different plants

• **Effects of higher precision manufacturing processes:**

- Less time and cost spent on trial series in production
- More parts pass inspection, fewer rejects, less scrap, less rework, less need for 100 % inspection
- Less process variation and improved consistency when manufacturing parameters are changed (e.g., improved tool change policy)

Costs of tighter tolerances and higher manufacturing precision:

- More precise machines and measuring equipment
 - More analysis and testing of the accuracy of machines
 - Improved environment
 - More skilled personnel
-

and engine power at no extra cost. This example shows that optimization of tolerances can result in a win-win situation¹⁵.

Key research challenges in area of precision and cost include the development of: (1) the data required to establish the relationship between precision and cost for different manufacturing environments, and for a variety of parts and machining processes; (2) procedures for cost-effective optimization of part tolerances and machine specifications; and (3) transfer mechanisms to enable small and medium manufacturing enterprises to choose a cost-effective strategy to achieve a given level of precision.

2. Key Challenges to the Discrete-Part and Machine Tool Industries

This Chapter examines more closely some of the trends in precision machining that present key technical challenges to the discrete-part and the machine tool industries.

2.1 Key Challenges to the Discrete-Part Industry

2.1.1 Part Accuracy

With Japan as pacesetter, global competition has lead to dramatically tighter tolerances for discrete parts. Such tight tolerances are required for interchangeability, automatic assembly, miniaturization, integration, design simplicity and improved product performance and reliability^{1,13-20}.

The importance of tighter tolerances to product competitiveness can be illustrated by some examples from the automotive industry. The perceived quality in the operation of an automobile door correlates with the force required to open the door. Variations in force correspond to variations in the dimensions of door assemblies, which, in turn, are affected by the precision of the dies used to stamp the door panels as well as the precision of the door assembly procedure. Swyt reports that U.S. cars require forces of $76 \text{ N} \pm 58 \text{ N}$ while their Japanese competitors require $31 \text{ N} \pm 9 \text{ N}$, a six to one advantage¹. In transmission components, more accurate profiles, decreased size variations, and reduced surface finish tolerances result in noise reduction, less wear, and improved fuel efficiency²⁰. Tighter tolerances on cylinder borings and pistons reduce blowby, tilting, and friction; thereby, improving efficiency and power, and reducing emission levels and wear.

2.1.2 Part Geometry

To reduce assembly efforts as well as the weight of products, expensive single parts with often complex geometries are used to replace assemblies^{21,22}. These parts require complicated manufacturing operations often executed by complex Computer Numerically Controlled (CNC) multi axis machine tools. The complicated geometry of the parts requires advances in in-process gauging techniques. Furthermore, to optimize the realized part accuracy, a better understanding of the accuracy of machine tools and machining processes is required than is presently available. Functional integration limits the possibilities of adjustment during assembly, thus, requiring more accurate features. As the demand for thinner and lighter parts increases, machining will become more difficult because of problems with part fixturing and chatter.

2.1.3 Quality Control

Historically, quality control and dimensional inspection have focused on post-process appraisal (i.e., finding defective parts after the fact). Post-process inspection has several shortcomings: (1) the manufacturing cost is already incurred when an error is detected, (2) it is often difficult to isolate the cause(s) of a defect, (3) there is a significant time lag between the discovery of a defect and the corrective action, and (4) the inspection and corrective actions are costly. A finished part is the outcome of many upstream processes and factors, for example fixtures, cutting tools and their settings, set-up procedure, programming, the machine tool and its controller, the manufacturing environment, the material from which the part is manufactured, and others. Inspection of a finished product or part is a validation that all potential sources of error are within tolerable range; however, it provides little information concerning which factor(s) is responsible for the observed defect(s), making the planning of corrective action more difficult²³.

Today the focus is shifting from post-process control to improved control of the manufacturing process itself through the use of deterministic manufacturing principles. Deterministic manufacturing is based on the premise that, in an automated environment, machines perform in a sufficiently deterministic manner to allow quality assurance through control of the process rather than post-process inspection²⁴. The process control ensures that the errors introduced by each machining process are within a tolerable range, regardless of the part(s) to be produced. With this approach, scrap, rework, lead time, and conventional inspection activities are reduced. To be successful, characterization techniques, models and sensors are required to monitor the accuracy of the manufacturing process, as well as the parameters that can be adjusted to improve accuracy. In the long run, it is far more cost-effective to invest in in-process measurement, control, and advanced machine tools, than in equipment that reveals defects and inaccuracies too late to prevent rejects or rework²⁵.

2.1.4 Automation

Due to the increased level of automation, machines are separated from human operators making direct human intervention difficult. This in turn means that manufacturing equipment must be reliable to avoid catastrophic failures and accidents. While operators supervise machines, they are no longer responsible for the quality of the manufactured products in the same manner as they were when the craftsmanship of the operator was the dominant feature in manufacturing. As stated by McClure, the effect of automation goes beyond a mere change in controlling intelligence²⁶. First, there is a difference in the structure that controls the size of the manufactured part, and, thus, accuracy (e.g., the substitution of the machine frame and scales for the hand-held micrometer). Second, automation enables complex operations where the traditional craftsmanship of the operator has a reduced effect (e.g., the traditional warm-up period of a machine has a reduced impact when, under numerical control, the spindle speed, and thus the heat generated, is continuously varied to maintain optimal cutting conditions). A significant impact of increased automation is that manufacturing processes become more deterministic and, therefore, can be controlled better.

2.1.5 Agile Manufacturing

Market demands are requiring high-volume manufacturers to provide more variety and faster model changeovers at decreasing cost⁷. As a result, there is an increasing emphasis on smaller and more varied batch-production runs. The need for faster changeovers in the automotive industry is illustrated in Figures 3 and 4. Inspection of Figure 3 shows that the number of car models has steadily increased over time, while inspection of Figure 4 shows that the volume of cars sold for each model has decreased over time. This volume is expected to be reduced tenfold over the next decade⁷.

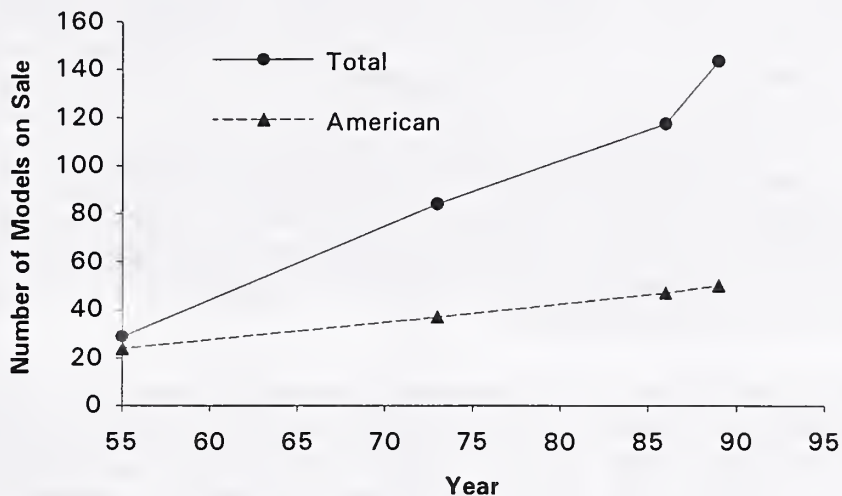


Figure 3. Fragmentation of the American Auto, Van, and Light Truck Market. Number of Automobile Models on Sale³.

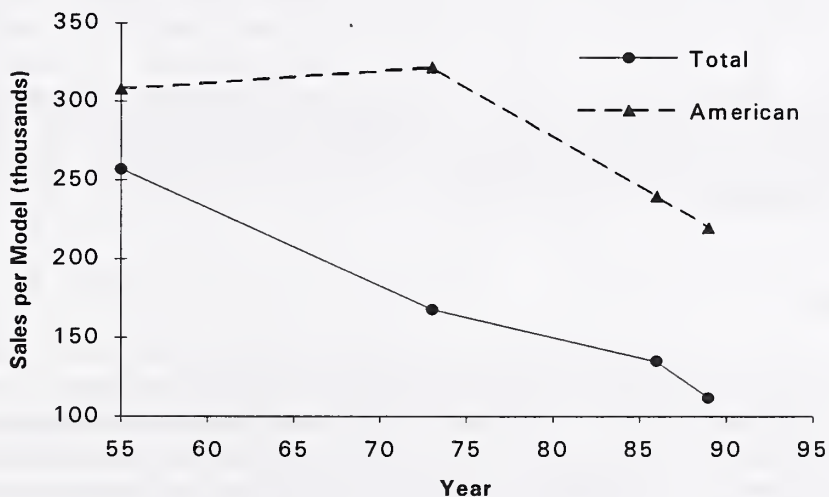


Figure 4. Fragmentation of the American Auto, Van, and Light Truck Market. Annual Sales per Model³.

The current state of the art in the automotive industry relies heavily upon transfer line technology. A traditional transfer line consists of a series of highly-specialized machine tools or transfer machines connected by a material handling system. It is designed to manufacture a specific model or a product line with minor variations. The specialized nature of transfer lines provides the highest levels of productivity and repeatability. However, when the model is phased out, the transfer line must be scrapped or rebuilt. The cost of retooling for another model can be as high as 90 % of the original cost⁷. Therefore, the high cost of transfer machines, typically between \$750,000 and \$1,000,000, can only be justified for high production volumes.

The key to meeting the market demands for fast changeovers is agile manufacturing (i.e., manufacturing technology able to quickly and economically reconfigure production facilities⁷). Agile transfer lines using modular units that can be quickly assembled and disassembled are required. It is expected that the use of multi purpose, multi axis machines that are able to make a large variety of different parts in a timely manner will increase. The rapid fabrication of production tooling (e.g., molds and dies) and part fixtures will have a high priority. Machining operations are more agile than casting and forming operations; accordingly, their use should increase as the demand for flexibility increases. Recent defense contract cutbacks caused a big increase in machining operations. When a major aerospace company built 800 planes a year, it fabricated parts using forming dies, but now that 100 planes per year is considered a big order, machining is more cost-effective²⁷.

Agile manufacturing is dependent upon the solution of several key technical challenges. First, as machines tools become more flexible, they also become more complex, yet precision must be maintained or improved for each of the ever increasing number of tasks required from any given machine. Accordingly, the design of agile high-precision machines and their maintenance becomes more difficult. Second, the practice of trial runs and iterative accuracy improvements is not cost-effective when batch sizes are decreasing and new products are introduced at increasing speeds. Accordingly, information about and improved control of the precision of each machine becomes more important. As mentioned previously, process control must ensure that the errors introduced by the machining process are within a tolerable range, regardless of the part(s) produced. This requires a shift from post-process inspection to in-process measurement and control as well as machine characterization. To accomplish these tasks, better sensors, measurement methods and interface standards are required than are now available. As more flexibility is built into manufacturing equipment, and as a larger variety of parts is produced in an arbitrary sequence, more robust predictive models for error compensation and quality control will be required.

2.1.6 Measurement

In small batch production, processes other than material removal will remain uneconomical for several decades²⁵. This means that, in the near term, better cutting tools, higher versatility, more rigid and better damped machines, as well as higher speeds and feeds are the probable avenues to higher efficiency. Fortunately, machines designed for high removal rates contain many technical similarities to machines designed for high accuracy²⁵. With the advent of fully automated manufacturing sequences, measurement must become an integral step in the manufacturing process. From a cost-effectiveness viewpoint, it is not desirable to wait until an

item has been completed to decide whether or not it is acceptable²⁵. However, measurements made during production must not interfere with the process.

2.1.7 Advanced Materials

Complex mechanical requirements can only be met by advanced or high-performance materials such as ceramics and composites. These materials exhibit favorable properties such as low wear and high strength under varied and adverse environmental conditions (e.g., high temperatures), or high strength and stiffness combined with low weight. Advanced materials are replacing traditional materials, such as steel and aluminum, in an increasing number of applications, as shown in Table 5.

Table 5
Airframe Materials Content (mass percentage)⁸

<i>Airframe</i>	<i>Design year</i>	<i>Aluminum</i>	<i>Titanium</i>	<i>Steel</i>	<i>Composites</i>
F-14 Tomcat	1969	39	24	17	1
F-15 Eagle	1972	36	27	6	2
F-16 Falcon	1976	64	3	3	2
F-18 Hornet	1978	49	13	17	10
AV-8V Harrier	1982	44	9	8	26
F-117A Nighthawk	1983	20	25	5	40
ATF Stealth	1989	20	25	5	40
A-12 Avenger II	1989	20	20	15	30
Boeing 757	1980	78	6	12	4
Boeing 757	1990	70	10	10	10
Boeing 757	1995	62	12	8	18

The full exploitation of the potential benefits of advanced materials requires adapted cost-effective machining processes which preserve the properties of the material while enabling the realization of complex, accurate forms with good surface finishes²⁸. High-performance ceramics, high-temperature alloys, metal-matrix composites and fiber reinforced plastics are examples of materials that have to be machined with either adapted conventional machining techniques or with entirely new machining processes. Currently, machining costs amount to a high proportion of the total manufacturing cost of products made from advanced materials. Machining costs need to be reduced if utilization of these materials is to be cost-effective. To achieve this goal, the complex interactions between machine characteristics, tools, workpiece material, and process parameters must be understood. Such knowledge will provide the technological basis and the infrastructure needed for the development of improved, cost-effective precision machining processes. New sensors must also be developed, for example to monitor the surface integrity of the machined material, as well as new interface standards.

2.1.8 Environmental and Safety Concerns

The increased concern over safety, product liability, environment, and energy consumption is compelling the manufacturing industry to take these factors into account in product design and manufacturing^{15,27,29-32}. This often requires that product components be manufactured to tighter tolerances. For example, emission levels and energy consumption of combustion engines are directly related to the accuracy built into engine components²⁰. Environmental and safety concerns have also provided an incentive to develop more environmentally friendly machining processes, often referred to as “green machining.” Both the internal environment of a manufacturing facility and its external environment must be considered. In the area of precision machining, the impacts of safety and environmental concerns include the substitution of hard turning with ceramic or CBN inserts for conventional grinding, which yields recyclable chips and fluids, and the increasing interest in dry machining and environmentally benign water-based coolants^{27,29,32}.

Each new process or process modification presents its own technical challenges. For example, dry machining means finding new ways to stabilize or compensate for the heat sources within the machine tool. It should be noted that the adoption of a technique designed to meet a safety or environmental challenge can also have an added-value on the manufacturing process. For example, enclosing a machine tool to protect workers from noise and hazardous emissions may increase the precision of the machine by protecting it from environmental temperature fluctuations. Thus, environmental, reliability, and safety concerns represent both a challenge and an opportunity.

2.2 Key Challenges to the Machine Tool Industry

While not all challenges faced by the discrete part industry are technological, some key technological barriers can be met through improvements in the primary tools, the machine tools, used in manufacturing products. Key challenges include:

- *Improved machine tool accuracy.* Accuracy improvements can be achieved through (1) better machine tool design and the selection of materials to minimize thermal and elastic distortions, optimize damping, and suppress vibrations; (2) the development and implementation of real-time error compensation methods for geometric, thermal, elastic, and dynamic errors, including the development of machine tool error models and fast characterization methods; (3) the development of robust adaptive process control methods, including the development of non-intrusive, in-process measurement and monitoring methods; (4) the development of improved, environmentally hardened sensors for in-process and process-intermittent measurement and control; and (5) development of interface standards for both sensors and controllers.
- *Improved throughput.* Throughput can be improved by high-speed spindles and increased speed and acceleration of feed drives. To achieve these goals, machine structures must be designed in such a way as to have low mass and high stiffness, high-speed high-acceleration axis drives and servos, low friction guideways (e.g., roller and ball bearings), and robust high-power, high-speed spindles. To accommodate higher spindle speeds, new

tool-holder/spindle interfaces must be developed that assure good tool positioning at high speed and, to be of practical use, be compatible with existing spindles and tool holders.

- *Increased reliability.* A key technique to improve the reliability of machine tools is predictive maintenance (i.e., the systematic servicing of equipment to reduce the possibility of failure)³³. Reliability affects the three key elements of competitiveness: quality, cost, and lead time. Well maintained machines hold tolerances better, help to reduce scrap and rework, raise product consistency and quality, and reduce downtime. By increasing uptime and yields of good parts, capital requirements are reduced and lead times shortened. Predictive maintenance is dependent upon obtaining reliable data. To obtain systematic reliable data, attention should be given to (1) the development of fast characterization methods for machine tools, (2) the development of methods to determine how often machine tools need to be characterized, (3) the development of methods to monitor machine condition, and (4) the development of sensors that allow for predictive control of such factors as machine wear, tool wear, and tool failure. In addition, self diagnostic techniques must be developed.
- *Improved flexibility.* To increase the ability of industry to respond quickly to new market demands, machines must incorporate increased flexibility. Increased flexibility can be achieved through the development of (1) robust, high-powered, open architecture controllers, (2) flexible and modular fixturing and tooling, realized directly from the product CAD data, (3) development of agile transfer lines in which modular units can be quickly reconfigured according to market demands, and (4) addition of more axes on machine tools. Each of these developments requires advances in machining to insure that accuracy is not sacrificed. "Live tooling" and fast tool servos are relatively new techniques in CNC turning that improve throughput, agility, and possibly accuracy. "Live tooling" is the addition of tool spindles to a lathe enabling multiple machining operations in one setup, (e.g., turning, milling, boring and grinding). Fast tool servos are used to synchronize the tool movement with the spindle rotation to enable the turning of asymmetric shapes, (e.g., pistons with an elliptic cross-section). The effects of "live tooling" and fast tool servos on machine errors, error characterization and compensation, and machine performance evaluation methods must be carefully evaluated.

3. Machine Tool Characterization

The field of machine tool characterization encompasses the parameters, test methods, models, and data analyses necessary to describe the performance of machine tools. In this report we consider only those characteristics that determine the accuracy of produced parts.

3.1 Overview

Machine tool characterization is important for the following reasons:

- It allows the specification of the mutual obligations, deliverables, and methods of verification between machine tool users and sellers;
- It allows performance comparisons between machines;

- It allows for a clear definition of the tolerance capability of a given machine. This is important (1) to select the most appropriate machine for a given job, (2) to assure the quality of manufactured parts, (3) to determine the cause of observed part errors and suggest corrective action, (4) to enable predictive maintenance, and (5) to assure compliance with standards on quality management which require that machine tool builders and users regularly test the accuracy of their machines (e.g., the ISO 9000 series³⁴);
- It provides the mechanism for obtaining the data required to devise and verify machine tool enhancement mechanisms such as geometrical and thermal error compensation, a topic that will be discussed in more detail in chapter 4.

The philosophy behind machine tool characterization is that, if a machine tool is properly characterized, then its performance for any task can be accurately predicted. In principle, quality control based on this philosophy, especially when combined with in-process measurement and control, allows for a significant reduction of post-process part inspection, scrap, rework, and lead time and facilitates the identification of the cause(s) of errors. Quality control based on machine tool characterization should be cost-effective, particularly in high-precision small batch manufacturing, and in the machining of complicated geometries.

However, on the shop floor level, regular machine tool performance evaluation is rarely practiced, especially in small- and medium-sized companies. A consensus has not been reached yet among builders and users of machine tools about either the need for or type of accuracy specifications required for machine tools. Most machines in the U.S. purchased by small companies are bought on the basis of the reputation of the manufacturer and personal contact, not specifications²⁵, a finding confirmed by the participants of the 1994 workshop on precision machining. Larger companies still routinely use cutting tests rather than instrumented tests. Many users feel that the documented tests do not reflect their needs and request customized tests focused on the intended application of the machine. The results are high costs, specification and intercomparison difficulties, disagreements between users and manufacturers, and often the selection of the wrong machine for a particular application. Furthermore, lack of machine tool characterization means that the user often has incomplete knowledge of the true capability of his machine, and of the machine performance variability with use. The results are increased costs and lead times for trial runs.

The lack of harmonization of both the terminology and data analysis methods used in various national standards further complicates the situation^{35,36}. For example, in different national standards the same terms may be used to describe different characteristics, while different terms are used for the same characteristics. This means ambiguities in interpreting quoted accuracies, and in determining the method used to test them. The differences between the various standards are often subtle, but can have dramatic effects. For example, the "positional accuracy" of a machine tool axis can vary by a factor of two to one depending upon which standard is used (e.g., the Japanese JIS³⁷, the German VDI³⁸, the American NMTBA³⁹ and B5⁴⁰, or the ISO standard^{41,36}).

Machine tool characterization is difficult because there are many geometrical, thermal, and dynamic sources of errors that can have complex interactions^{25,42}. The major sources of errors in machine tools are listed in Table 6. Machine tool testing and characterization is time

consuming, expensive and requires trained staff. The amount of data gathered is voluminous even when testing is limited to the no-load state of the machine (i.e., the geometrical errors). Accordingly, analysis is complicated, a problem further aggravated by the three dimensional nature of machine tool errors, the large variety of tasks typically executed by any one machine, the complex error introduction and propagation which are dependent on the task, and the large number of variables that define each task. To be useful, the performance evaluation has to provide sufficient data to allow for an accurate budgeting of errors, and to predict the error bounds for typical tasks. The problem is further aggravated by difficulties in translating machine tool performance parameters into actual machined part errors, except for cases where tooling is particularly simple²⁵.

3.2 Metrological and Technical Challenges

Most experts agree that, while much progress has occurred in the field of machine tool characterization, characterization remains an expensive, time-consuming endeavor that is beyond the reach of small- and medium-sized enterprises. Key metrological and technical challenges in this area are listed below.

1. Development of fast, in-situ, practical machine tool characterization procedures. These procedures, and the related data analysis, should be user-friendly, should lead to a significant decrease in the time and equipment required to characterize machine tools, and yield meaningful accuracy parameters.
2. Identification of key environmental factors and process variables that affect machine tool accuracy.
3. Determination of short but comprehensive duty cycles that show the effects on machine tool accuracy of the parameters identified in 2 above.
4. Determinations of how often and what kind of machine tool evaluations are required for a variety of machines and production environments.
5. Development of methods to translate machine tool performance parameters into machined part errors.
6. Development of methods to translate design tolerances into required machine tool performance parameters.
7. Development of the data needed to insure that machine tool characterization standards are based upon the state of the art.
8. Identification of the machine tool features required to facilitate performance evaluation.
9. Expansion of current research on machine tool characterization to include a larger variety of machines, and dynamic conditions.

Table 6

Classification of Major Machine Tool Errors

- **Quasi-static Machine Tool Errors:**

- errors due to the limited geometric accuracy of machine components in a certain reference state,
 - axis position measurement system,
 - straightness of guideways,
 - roll, pitch, and yaw,
 - squareness and parallelism of machine axes
- errors due to slowly varying forces,
 - dead weight of moving machine components,
 - workpiece weight,
 - clamping deformations
- errors due to thermally induced strains in the machine structure resulting from internal and external heat sources,
 - environment,
 - spindle drive,
 - axis drives

- **Dynamic Machine Tool Errors:**

- spindle error motions,
- errors in the coordination of axis motion caused by imperfections of the controller,
- both self-induced and forced vibrations

- **Workpiece and Tooling Errors:**

- chucking and fixturing,
 - tool wear and tool setting,
 - material stability and residual stresses.
-

10. Incorporation of the cutting process into the machine tool characterization method.
11. Development of error budget procedures for machine tools and machined parts.
12. Development of diagnostic measurement methods to enable predictive maintenance, including development of appropriate sensors.

4. Machine Tool Performance Enhancement*

In the context of this report, the treatment of machine tool performance enhancement is limited to the improvement of precision (i.e., error reduction).

4.1 Overview

Techniques for error reduction can be classified into two groups: error avoidance and error compensation²⁵. Error avoidance is based upon reducing the error sources (e.g., reducing heat sources) and reducing the sensitivity of the machine to these sources (e.g., using thermally invariant structures). Error compensation attempts to cancel an error by predicting it and embedding a corrective action. Using suitable sensors and a model for the error propagation mechanism, the input or output of the machine is altered to eliminate the error.

Error compensation techniques can be subdivided into two groups: precalibrated error compensation and active error compensation. When a precalibrated error compensation strategy is utilized, first the errors are predicted based on a machine tool model estimated prior to the start of the machining process. Once errors have been predicted, corrections are provided by either modifying the software for the part program or by adjusting the movement of the machine axes through the machine controller. It should be noted that the machine tool model can be constantly updated using new error data obtained by machine performance evaluation, and post-process, process intermittent and in-process measurements.

When an active error compensation approach is used, the measurement and error compensation occur simultaneously. For example, a caliper arrangement may be used to measure the workpiece diameter during turning and grinding. The data obtained are sent to the controller which alters the position of the relevant machine axis to compensate for the observed errors. The major advantage of active error compensation is that it does not rely on either the short- or long-term repeatability of the machine, nor does it require extensive error assessment and modeling. However, except for very simple prismatic features (e.g., diameters), the practical application of active error compensation is limited by the availability of cost-effective, factory hardened, non-intrusive sensors that measure either the workpiece errors or the errors in the realized position of the tool during machining.

Machine tool retrofit is also an important aspect of machine tool enhancement as the U.S. inventory includes many older machines, which are basically sound. In 1980 the U.S. ranked lowest among the major industrialized nations in terms of the percentage of machines less than 10 years old²¹. During the 1980s the U.S. machine tool base aged significantly. The average age of metal-working machine tools has reached a 53-year peak of 10 years. The

mechanical structure of U.S. machine tools is of high quality. Therefore, it is cost-effective to retrofit these machines by taking advantage of error compensation and by updating certain critical components, such as the controllers and the axis drives.

4.2 Metrological and Technical Challenges

Error compensation can be a reliable, flexible, and cost-effective method to improve the accuracy of machine tools. However, its application suffers from the many problems of machine tool performance characterization discussed in Section 3. Key metrological and technical challenges in this area are listed below.

1. Research on precalibrated error compensation should be continued. More attention should be given to error avoidance techniques and active error compensation. Special emphasis should be placed on developing methods to suppress vibrations.
2. Error compensation research should be performed on a larger variety of machines.
3. Develop more reliable techniques to incorporate into error compensation the wide variety of environmental conditions encountered in industrial settings.
4. Continue research on machine tool retrofit, including the development of open-architecture controllers.
5. Document the complete error compensation procedure used on various machine types in real production environments. Documentation should include all steps (e.g., error assessment, error modeling, used sensors, implementation in controller, problem areas and evaluation of results, including cost).
6. Develop the data required for the development of procedures that enable the generalization of error models across different machine tools of the same type in different environments.
7. Develop procedures for machine tool design, manufacturing and maintenance that take into account the benefits and limitations of error compensation.
8. Identify key machine tool design features and manufacturing procedures that reduce performance variations across machines of the same type.

5. Closed-Loop Precision Manufacturing

The term closed-loop precision manufacturing refers to a systematic approach in which information obtained during, in between, and after manufacturing operations is used in feedback loops to control the accuracy of manufactured parts. The concept of feedback is not new in manufacturing⁴³. In high-volume production, post-process inspection combined with Statistical Process Control (SPC) techniques are used to determine when intervention in the

manufacturing process is required based on trends in the observed quality of finished products.

5.1 Overview

As discussed in section 2.1.3, quality control based upon post-process inspection alone has several drawbacks as trial runs and iterative accuracy improvements result in relative high costs and long lead times. When several machines and setups are involved in the manufacture of a product, the error diagnosis, the identification of corrective measures, and the determination of intervention strategies are difficult, time consuming, and often unreliable. Therefore, a process control strategy which does not uniquely rely on post-process inspection is preferable. This can be achieved by a control strategy that focuses on maintaining and improving the precision of each device used to manufacture a part such that accurate parts are manufactured *the first time*.

Machine-based quality control exploits the concept of deterministic manufacturing. It is based on the premise that most errors in the manufacturing process are repeatable and predictable. Therefore, errors can be predicted and compensated²⁴. Thus, the quality of "arbitrary" products can be assured by controlling both the manufacturing process and the equipment used. This is achieved by statistical process control methods, in-process measurements and control, error compensation, and process intermittent and post-process inspection.

At the core of a machine-based quality control strategy is an error model of the machine. This model can be used to predict the accuracy of manufactured workpieces, to compensate machine errors, to adjust manufacturing parameters, or to determine when and how the machine should be serviced. The model is developed using data from a detailed machine performance evaluation. The model is continuously upgraded as more data become available. This upgrade can be achieved using several feedback loop mechanisms, as shown in Figure 5. The mechanisms include:

- *Real-time control loop* – a process in which the machine tool and the machining process are both continuously monitored. The data, obtained in real-time, are used to modify the tool path and process parameters (e.g., feed rate and spindle speed) during the machining to achieve higher accuracy and surface quality. Monitoring is done by sensors that are incorporated into the machine tool and measure key parameters; for example, position, temperature, force, vibration, sound emissions and surface finish.
- *Process-intermittent control loop* – a process in which information on dimensional accuracies of the semi-finished workpiece is obtained without removing it from the machine. This information is used either to adjust the part program for the final cut or to modify the error compensation model. For example, the workpiece errors can be measured by replacing the cutting tool with a displacement probe system, that is, in effect, temporarily transforming the machine tool into a coordinate measuring device. This approach yields valuable information on non-repeatable errors, errors associated with the cutting process (e.g., cutting forces, heat due to cutting, and tool setup and wear), and errors that are known but too complex for real-time software compensation during machining.

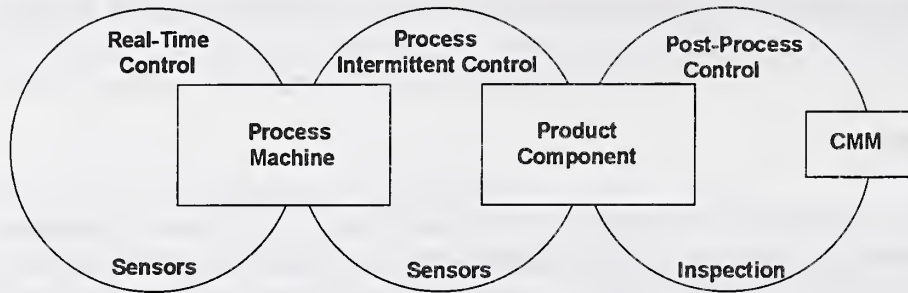


Figure 5. Feedback in Closed-Loop Precision Manufacturing⁴⁴.

- *Post-process control loop* – a process in which information about the accuracies realized in the finished workpiece is obtained independently from the machine tool, for example, by means of a Coordinate Measuring Machine (CMM). This information provides the data required to check, update or modify the machine tool model, and to determine whether the machine performance characterization is out of date. In addition, post-process inspection data can provide important information about errors that are primarily dependent upon the properties of the workpiece rather than the machine. Included are errors originating from part geometry, workpiece material, and fixturing (e.g., the elastic distortion of thin-walled workpieces due to fixturing).

5.2 Metrological and Technical Challenges

Closed-loop precision manufacturing is key to achieving significant improvements in manufacturing. Metrological and technical challenges in this area include:

1. Identification of key machine performance indicators that correlate best with the precision of the machined parts (e.g., acoustic emission, vibration, force, temperature, etc.).
2. Development of reliable, non-intrusive, factory-hardened sensors.
3. Development of sensors and measurement procedures to determinate the precision of the machined parts in-process and independently of the machine precision.
4. Development of sensors to detect tool wear and procedures for real-time compensation.
5. Development, in cooperation with industry, of sensor and controller interface standards.
6. Development of methods to shutdown machine tools when prescribed limits of indicators described in 1 above are exceeded, and to present diagnostic information.
7. Development of the architecture required to process feedback data to update error models, and to implement these into controllers.
8. Testing of closed-loop precision manufacturing concepts across a variety of machines types and industrial settings.

6. Process Modeling

6.1 Introduction

Process modeling is an attempt to describe in mathematical terms the interactions that occur between the tool and the workpiece during cutting. Process models are used to predict and optimize cutting performance, with a minimum of, or without, application-oriented cutting tests. The parameters included in these models are shown in Figure 6. Dependent variables include types of chips produced, cutting forces, energy consumption, temperature of the workpiece, tool and chips, surface finish, surface integrity, residual stresses, size of the machined workpiece, and tool wear and failure¹². The primary reason for the development of process models is to improve the material removal rate while keeping the above dependent variables at acceptable and predictable levels. The increased use of advanced materials requires significant advances in process modeling.

To verify and improve process models, data must be obtained while cutting is occurring. The unavailability of suitable sensors which can withstand the harsh cutting environment coupled with the lack of interface standards make this task difficult to accomplish. The problem is compounded by the fact that little data exist about which parameters best predict performance. The cutting phenomena are extremely complex because of the large number of independent variables that must be considered in the optimization of the dependent variables. The major independent variables include workpiece material and geometry, type of machining process, the material, geometry and condition of the tool, the cutting fluid, the cutting conditions such as cutting speed, depth of cut, and feed rate, and the characteristics of the machine tool, especially its (dynamic) stiffness and damping.

The reluctance to apply process models, and related technology, on the shop floor can be seen in the results of a survey of attitudes and practices in the end-milling of aluminum among machinists and programmers⁴⁵. One of the most significant findings is that both NC programmers and machine operators are reluctant to change and adopt new technology. Indeed, the survey revealed that most NC programmers adopt a conservative spindle speed and feed rate for each type of cut (e.g., roughing, finishing, cornering), independently of cutter size, cross section of cut, and workpiece material. Operators often reduce the programmed speeds by as much as 50 % to 60 %. Some of the reasons given for these conservative practices include the tendency to program the same speed and feed, excessive noise, problems in cleaning chips, anticipated maintenance problems, and the insecurity associated with going fast. The survey showed that, at least in the aerospace industry where the raw workpiece is expensive, the fear of workpiece spoilage is a real deterrent to higher material removal rates, particularly among shop-floor personnel. It appears that once a part is produced that passes inspection, very little, if any, process optimization is pursued. These findings were reaffirmed during the October 12, 1995 workshop. Overcoming the reluctance to adopt new technology is very important as adoption of process modeling, process optimization, and associated technology innovation is a key ingredient for increased productivity.

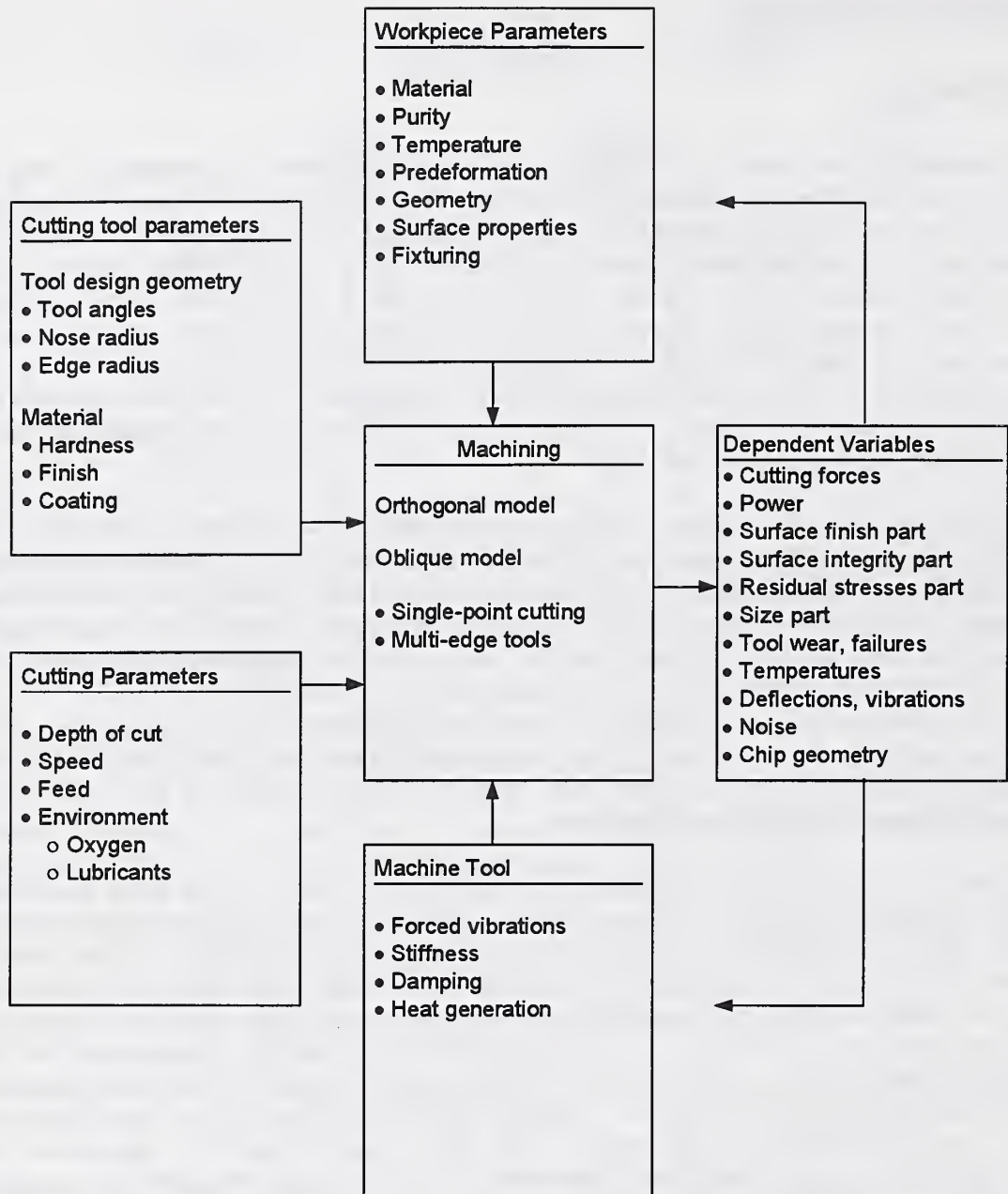


Figure 6. Simplified Presentation of the Input/Output Relationships in Cutting (adapted from Davis¹²).

6.2 Chatter

Chatter is self-excited vibration caused by interactions of the chip-removal process with the machine/tool/workpiece system. The vibration amplitude is usually high, resulting in visible marks on the workpiece surface and accelerated tool wear. Chatter begins with a disturbance

in the cutting zone such as an inhomogeneity in the workpiece material or surface, machine vibration, a change in the type of chips produced, or a change in friction (e.g., change in coolant effectiveness)⁸.

The most important type of chatter is regenerative chatter. It has long been recognized as the most important factor in limiting production rate⁵⁰. The impact of regenerative chatter is particularly noticeable when machining thin webs with slender tools. Regenerative chatter occurs when a tool cuts a surface that has incurred a roughness or disturbance from the previous cut. As a result the depth of cut varies. This in turn causes variations in the cutting force which themselves lead to tool vibrations. As the process repeats itself, it can become unstable, resulting in unacceptable surface quality and possible damage to both the tool and the machine. Chatter becomes more critical when machining materials that are difficult to cut or workpieces and tools with low stiffness. Some advanced tool materials require strict chatter control to prevent brittle breakage. Increased machine tool agility increases the risks of unstable conditions.

Chatter can generally be controlled by increasing the stiffness and damping of the system. Machine tool stiffness varies with frequency. Therefore, changes in cutting parameters, such as cutting speed, can influence chatter and shift the system into a stable region. Chatter vibration has been analyzed extensively. Theoretically, it is possible to predict stable process parameters from a knowledge of the compliances and damping factors of the machine structure, tool, workpiece, and the cutting process^{46,47}. These data can be obtained by measuring the dynamic characteristics of the workpiece/tool/machine system (e.g., by experimental modal analysis). However, the dynamic characteristics of the system are sensitive to the position of the machine tool axes, the workpiece properties, the cutting conditions, and the tool, especially the edge shape. Accordingly, modeling of the system is complex when all the tasks that the machine is capable of doing must be accounted for. Because of the proximity of the machine/tool/workpiece dynamic modes, finding optimal cutting conditions is difficult.

Systems are being developed to automatically adjust the machining parameters to avoid chatter. Using sensors (e.g., force dynamometers, accelerometers and microphones), these systems detect chatter and adjust the process parameters until a stable region is reached⁴⁸. The effective signal-to-noise ratio is typically low due to the significant amount of background noise. Modern signal processing techniques have not been applied to the fullest extent possible.

An alternative strategy is to reduce chatter without changing the process parameters. In the past much attention has been focused on minimizing the chatter problem by improving the dynamic compliance of the machine/tool/workpiece system. This is achieved by a variety of mechanisms such as increasing the system structural damping, its rigidity, or by adding vibration absorbers. Some modern approaches under development include (1) use of milling cutters with uneven insert spacing that reduce the periodic component of the cutting force, (2) the continuous variation of spindle speed as a means of reducing the periodic chip loading⁴⁹, and (3) active damping⁵⁰. Active damping remains a controversial issue, and may be useful in only a limited number of applications. To render modern chatter reduction systems practical, the systems must become more reliable and flexible.

6.3 Tool Wear and Failure

Tool wear occurs because cutting tools are subjected to high localized stresses, and sliding of the chip along the rake face and of the tool flank across the freshly cut surface⁸. Plastic shearing of the workpiece material and friction increase the temperature at the tool tip. The increased temperature accelerates the physical and chemical processes associated with tool wear. Several wear mechanisms can operate simultaneously. These mechanisms include adhesion, abrasion, oxidation, diffusion, solution, fatigue fracture, superficial plastic flow, and plastic collapse⁴⁶. Tool wear changes the geometry of the tool and alters the state of stress and strain in the cutting region. This in turn changes the cutting forces and the mechanics of chip formation. Dimensional accuracies and surface finish of the manufactured parts are degraded. In addition, severe wear can weaken the tool whose edge may suddenly fracture. Catastrophic tool failure may cause significant damage to the workpiece.

The rate of tool wear depends on many factors. These include tool and workpiece materials, tool geometry, cutting fluids, process parameters (e.g., cutting speed, feed, and depth of cut), rigidity of the machine/tool/workpiece system, and the positioning of the tool. Information about the rate of tool wear is critical in selecting the right tool for a given job and the appropriate process parameters, and to identify how often the tool must be changed. Information about tool wear can be obtained using models. It usually is reported in tool wear charts.

The importance of tool wear monitoring should not be underestimated. Tool wear monitoring techniques fall into two categories, direct and indirect. The direct method involves the measurement of the wear by periodically observing changes in the tool profile (e.g., using a toolmaker's microscope or an automated vision system). Although reliable, this approach requires that the cutting process be interrupted. Indirect methods of monitoring wear involve the estimation of tool wear based on real-time data of process variables such as force, vibration, acoustic emission, power, temperature and surface finish. In-process monitoring is more desirable but more difficult to achieve.

6.4 Metrological and Technical Challenges

Process modeling is an attempt to describe in mathematical terms the interactions that occur between the tool and the workpiece during cutting. Process models are used to predict and optimize cutting performance, with a minimum of, or without, application-oriented cutting tests. Key metrological and technical challenges in this area are listed below.

1. Development of procedures for increasing accessibility of state of the art process models, machinability data, and process optimization techniques.
2. Development of the basic knowledge, databases, and models required to describe the complex interactions between machining characteristics, tools, workpiece material, and process parameters needed for cost-effective machining of advanced materials.
3. Investigation of the applicability of modern analysis techniques such as nonlinear dynamics, neural networks, expert systems and molecular dynamics.

4. Development of sensors to monitor and optimize the machining of advanced materials. Special attention should be given to monitoring surface integrity.
5. Determination of machining on residual stresses and their effects.
6. Development of measurement techniques to assess quickly the machine/tool/workpiece dynamic properties required to select stable process parameters.
7. Development of sensors, actuators, process optimization schemes, and adaptation of modern signal-processing techniques to monitor the process and reduce chatter.
8. Development of improved wear models and reliable, non-intrusive, and robust tool wear monitoring and compensation systems.
9. Development of tougher, more refractory tool materials and coatings, especially for high-speed machining and the machining of advanced materials.

7. Emerging Processes

In this chapter some emerging machining processes are described. Some of the challenges and opportunities they offer are discussed briefly. Research needs are not considered here, except in the case of high-speed machining, because they will be the object of a separate workshop and report.

7.1 High-Speed Machining

7.1.1 Overview

A logical definition of High-Speed Machining (HSM) is machining at a speed significantly higher (say, an order of magnitude or higher) than the speed commonly in use on the shop floor⁵¹. The precise definition in terms of cutting speed is difficult, however, because of the vastly different speeds at which different materials can be machined with an acceptable tool life. For example, it is easier to machine aluminum at a cutting speed of 1800 m/min than titanium at 180 m/min⁵². To illustrate this fact, the range of cutting speeds for high-speed milling of different materials is presented in Figure 7. Regardless of speed, a common characteristic of high-speed machining is a small depth of cut⁵³. The resulting low chip loads, further decreased by a local softening of the workpiece material at the elevated cutting zone temperature, allow high material removal rates without sacrificing accuracy and surface quality. High-speed machining cells can often process parts three to five times faster than conventional machining at 30 % to 40 % lower cost⁷.

Further benefits to be derived from high-speed machining include:

- *Reduced chip loads.* The reduction in chip loads leads to higher machining accuracy, improved surface finish, and reduction of residual stresses, especially when machining thin webs. For some materials (e.g., Teflon) the chip load is further reduced by the favorable change in material properties that occurs at the high strain rates associated with high-speed machining.
- *Lower workpiece temperature.* As the cutting speed increases, a higher percentage of the heat generated by the process is carried away by the chips, reducing the temperature of the workpiece and the rate at which the tool temperature increases^{12,45,52}. Furthermore, the power required to achieve a given material removal rate decreases with higher cutting speeds⁴⁵. The lower workpiece temperature provides for better surface finishes, reduces the damaged layer, and causes less thermal expansion and warping of thin walled workpieces.
- *Chatter prevention.* High-speed machining is often used in applications where there is a lack of stiffness in the machine/tool/workpiece system, as in the end milling of thin walled and pocketed aircraft aluminum structures⁵³. Machining these parts, often with slender tools, involves low stiffness of both tool and workpiece, which results in severe limitations of cutting stability. To avoid chatter, one alternative is to use very-low cutting speeds, and machine the workpiece in the range of strong process damping. However, this approach results in low material removal rates. The other alternative is to use a very small depth of cut to avoid chatter and high cutting speeds and feed rates to achieve economic material removal rates. There is evidence that, at higher speeds, the "chatter-free" stability lobes are more profound, enabling a further increase in material removal rate⁴⁷.

The use of high-speed machining technology in industry has been made possible by the development of tougher, more refractory tool materials, and the advent of reliable high power, high-speed spindles which can achieve speeds in the order of 10,000 rpm to 100,000 rpm. The

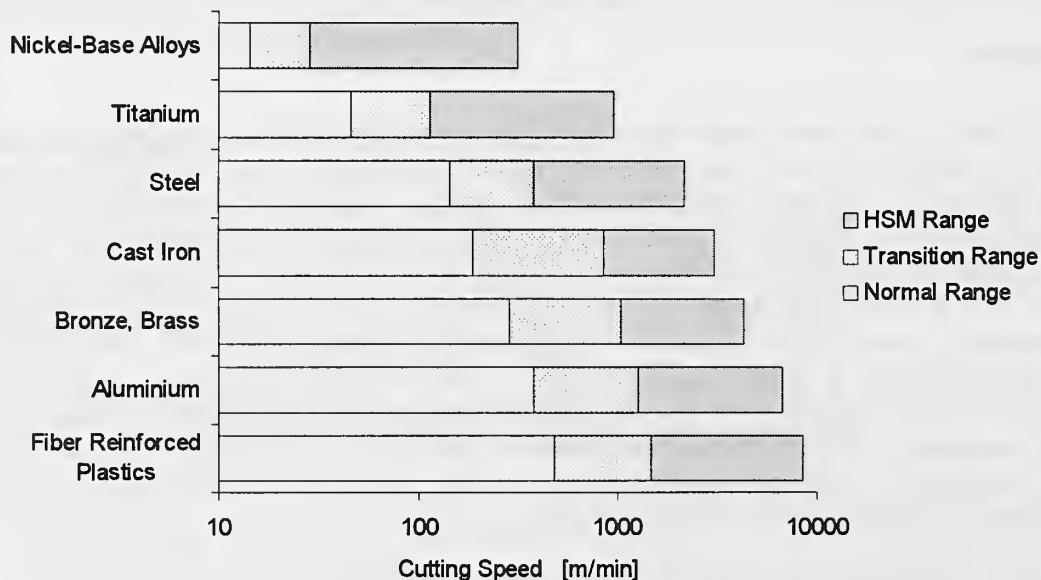


Figure 7. Range of Cutting Speeds for High-Speed Milling⁵².

highest practical cutting speed for many difficult-to-machine materials (e.g., hardened steels, nickel base superalloys, and titanium alloys) is, however, still severely limited by the nonavailability of tool materials that will last over a sustained period of time at high speeds⁵¹. It is generally agreed that the cutting temperature increases with an increase in cutting speed except for relatively easy-to-machine materials such as aluminum¹². At these elevated temperatures, wear by chemical dissolution of the tool material into the chip becomes dominant in contrast to wear by abrasion in the normal regime. High pressure jet cooling systems can reduce the tool temperature while assisting chip breaking and evacuation. There does not appear to be a maximum speed limit for easy-to-machine materials because the maximum tool temperature, limited by the melting temperature of the work material, is below the temperature at which serious wear occurs. In the case of aluminum, the low tool temperatures enable the use of carbide tools which results in greater stiffness and smaller tool deflections⁵¹. A possible limiting factor in high-speed machining is the high energy required to accelerate the chip past the shear zone, which is proportional to the third power of the cutting speed⁵².

7.1.2 Metrological and Technical Challenges

There exist several metrological and technical challenges in the application of high-speed machining. These include the development of:

1. Tool materials that last for a sustained time at high cutting speeds.
2. High-power and high-speed reliable spindles (e.g., air, magnetic, or hybrid angular ball bearings). Attention should be given to lubrication, heat generation, centrifugal forces, and dynamic aspects in the development of these spindles.
3. Fast feed drives and suitable guideways to achieve the required high accelerations and speeds (e.g., linear motors and multiple thread roller drives).
4. Machine tools with a minimum number of moving parts and lightweight, high stiffness, structures to achieve high accelerations (e.g., composites, thin walled steel, titanium, and aluminum).
5. Controllers that allow fast cornering and are able to handle large amounts of CNC code in a timely manner⁵⁴.
6. Schemes to reduce the required amounts of CNC code⁵².
7. Alternative tool holder interfaces designed for high stiffness and axial positioning accuracy at high speeds⁵². Recently a new interface was introduced in a Standard^{55,56} that is the object of some controversy as it is likely to lead to complex designs and incompatibility with current tools and spindles⁵⁷.
8. Active and passive devices to ensure the safety of the operator and the machine.
9. Efficient chip removal techniques.

7.2 Hard Cutting

Hard cutting is the cutting of heat-treated hardened (50 Rc to 65 Rc) steel parts, usually with ceramic or Cubic Boron Nitride (CBN) tool inserts, on rigid standard or custom build machine tools⁵⁸. Hard cutting has been used for turning, milling, boring, and broaching⁵⁹.

As machine tools and tooling are improved, hard cutting operations are slowly replacing conventional grinding techniques in the manufacture of hardened steel components, particularly in the automotive industry. Hard cutting results in higher production rates, lower cost per part, and significantly less costly machine tools⁵⁸. Multiple operations can be performed in one chucking, which improves accuracy and throughput. Furthermore, a more complex geometry can be achieved in a flexible manner on standard CNC machine tools, without customized tooling as in form grinding. This makes the technique suitable for prototyping and low volume batch production (e.g., the machining of roller bearing prototypes and complex molds for lenses). Hard cutting is an environmentally more friendly process than grinding, as the disposal of cutting waste, often limited to recyclable chips, is easier than the disposal of grinding swarf and lubrication fluids²⁹.

Although hard cutting is a cost-effective alternative to grinding, the realized tolerances and surface finishes do not yet match those that are achieved by grinding. In some cases, however, better tolerances and finishes are achieved because some of the defects associated with grinding, such as wheel lobing, are eliminated. Tool life and associated process consistency are key barriers. Hard cutting involves high tool tip temperatures and high cutting forces which promote tool wear and chatter. The substantially higher cutting and thrust forces require adequate power and high machine, tool, and workpiece stiffness. Furthermore, the adverse effects of the process on the integrity of the workpiece surface has to be avoided. Nevertheless, with precise feed rate and high stiffness, hard cutting may offer an efficient alternative to abrasive machining.

7.3 Thermally Assisted Machining

Generating ductility is essential for the machining of advanced materials such as ceramics and hardened steel. When using tools with defined cutting edges (e.g., turning), the tool induced heat may be insufficient to achieve the required softening of the workpiece material in the cutting zone. Therefore, researchers are working on the applications of external energy sources such as a laser or plasma arc to heat the material in the area of the chip root^{28,45}. In addition to enabling cutting, the added heat lowers cutting forces and power requirements. Furthermore, improved surface finish and integrity, increased tool life, and higher material removal rates have been reported. With laser technology, the heat energy can be controlled and the heat-affected zone can be closely limited to the shear plane, with minimal heating of the material that is in contact with the cutting tool and the outer layer of final workpiece surface. Jet engine manufacturers, for example, show great interest in this technology as more emphasis will be placed on the use of high-resistance materials in turbine engines²⁸. It should be noted that this technique is relatively new and its application for various materials and machining tasks requires further investigation. Furthermore, the adverse effects of the extra heat input on thermal deformations requires attention.

7.4 Dry Machining

Cutting fluids, or coolants, are used extensively in machining, mainly (1) to reduce friction, wear, and built-up edge formation, thus, improving surface finish and tool life; (2) to reduce the cutting forces and energy consumption; (3) to cool the cutting zone, machine, and workpiece, which itself reduces thermal distortions, tool wear, and layer damage; (4) to wash away chips and swarf; and, (5) to protect the newly machined surface from environmental corrosion⁸. With the passage of the Resource Conservation and Recovery Act of 1976 and the increasing concern with environmental issues, coolant disposal prices have skyrocketed. As a result, coolant recycling and management have become a major concern⁶⁰. An alternative is to use no coolant at all. Dry machining has the additional advantage of yielding dry chips that are more amenable to recycling than wet chips. In addition, workpieces produced with dry machining can be more easily cleaned, and coolant-related costs avoided.

However, to date, several technical barriers stand in the way of a widespread application of dry machining. A quantitative comparison of the severity of various machining operations is shown in Table 7. The severity is determined by the magnitude of the temperatures and forces encountered, the tendency of built-up edge formation, and the ease of chip disposal. Inspection of Table 7 indicates that as severity increases, the need for an effective cutting fluid increases. The development time to implement dry machining for the relatively easy-to-machine aluminum, as estimated by a major car manufacturer, is shown in Figure 8.

To maintain machining precision with dry machining, several key challenges must be met. The absence of lubrication and cooling results in poorer surface quality and poorer process consistency. Furthermore, dry machining results in higher machine, tool and workpiece temperature fluctuations which require further error compensation and avoidance measures. Coolants are used to remove both the heat generated by the machining process and the internal machine heat sources (e.g., the spindle drive), and to stabilize the machine temperature in response to environmental temperature variations. Both changes in machine temperature and thermal gradients in the machine structure cause significant errors. Accordingly, mechanisms must be developed to overcome these problems.

7.5 Ultrasonic Machining

Ultrasonic machining is a process that uses the ultrasonic vibration of a tool to machine hard, brittle, nonmetallic materials¹². Advanced materials such as ceramics and composite materials, and glass are both hard and electrically nonconductive. They require alternative machining processes. This has encouraged the use of ultrasonic abrasive machining. In ultrasonic machining, the tool, driven by vibrations, strikes the abrasive particles contained in the carrier liquid, while the particles are in contact with the part. The workpiece material is mainly removed by microchipping or erosion with the fine abrasive grains. Complex cavities can be generated by a single pass in a procedure similar to Electro Discharge Machining. Next to grinding, ultrasonic machining is probably the most frequently used method to machine advanced ceramics. Technical challenges in this area include low material removal rates, that may be increased by special fluids and higher vibration frequencies, tool wear, and an insufficient understanding of the micro-phenomena that occur at the part/tool interface.

Table 7

Relative Severity of Machining Operations⁸.
The higher the severity the greater the need for an effective cutting fluid.

Cutting Operation	Operation Severity	Cutting Speed	Cutting Fluid Activity
	High		High
Broaching (internal)	↑	↓	↑
Tapping			
Broaching (surface)			
Form and thread grinding			
Threading (general)			
Gear shaping (rotary)			
Thread rolling (rotary)			
Gear shaping			
Reaming			
Deep drilling			
Drilling, boring			
Thread rolling (rack)			
Hobbing, gear (spline)			
Milling			
Turning			
Band and hack sawing		↓	
		High	

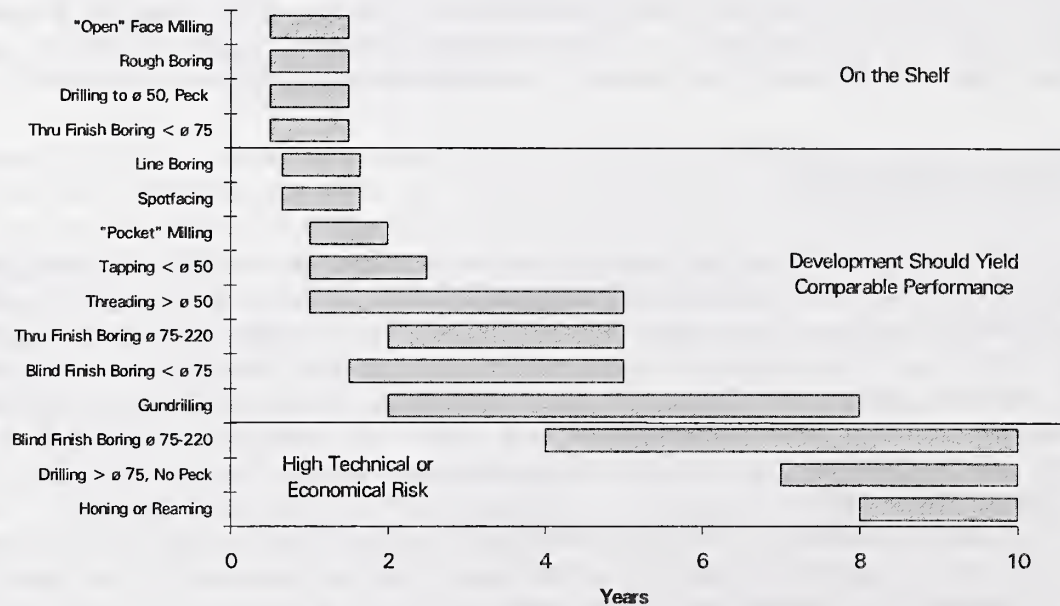


Figure 8. Estimated Development Time to Dry Aluminum Production¹⁵.

Ultrasound may be used also to assist machining processes⁶¹. The vibration improves the distribution of the cutting fluid, facilitates the removal of swarf and chip breakage, assists the fracturing of brittle workpiece materials, and reduces cutting forces, tool wear, cutting temperature, built-up edge, and work-hardening of the workpiece material. When machining composites, ultrasonic tool vibrations may assist the cutting of the individual high strength fibers without tearing holes in the structure²⁸. Applications of ultrasound have been reported in turning, drilling, tapping and grinding⁶¹.

7.6 Ultraprecision Machining

Ultraprecision machining refers to the machining of components with micrometer or submicrometer dimension and form tolerances, and surface roughness to within a few tens of nanometers. Ultraprecision machining is required for the production of mirrors (e.g., scanner mirrors and aluminum substrate drums in photo copying machines), optical parts with sophisticated form and extremely high geometric and surface quality, microgrooves, and mirror finishing of brittle materials⁶².

Due to the extremely high accuracies involved, special measures are required regarding the machine tool (e.g., high-accuracy spindles, high-accuracy friction drives, piezo microfeed devices, and error compensation and avoidance), the cutting tool, the controller, machine tool metrology, chip control, working materials, the environment, and suitable machining strategies. Many of the tools and insights used to advance the precision of "ordinary" machining have their roots in ultraprecision machining.

While important, ultra precision machining is not covered in this report.

7.7 Material Ingress Manufacturing

Material ingress manufacturing is a term used to describe manufacturing techniques in which the part is produced or modified by gradually growing material to the required shape⁶³. Material ingress includes desktop manufacturing, direct CAD manufacturing, solid freeform fabrication, material deposit manufacturing, layer manufacturing, and rapid prototyping. Material ingress manufacturing is used for small batch sizes and rapid prototyping, often directly from the geometric description of the product. Although not part of the family of machining, these techniques are important for machining because they may represent a breakthrough in manufacturing comparable to the advent of numerical control in traditional applications of machining such as rapid prototyping, small batch production, and tooling fabrication.

Fabrication of tooling (e.g., molds and dies) and the associated testing and "de-bugging" is the last phase of production preparation. When fabrication of tooling begins the design phase has been finished but actual production cannot start until the tools have been fabricated. The machining of hard tool steel is a time consuming and expensive process. Reducing this time is of critical importance. Ingress manufacturing techniques have the potential of revolutionizing the manufacture of tools. Examples are the use of the ingress manufactured parts as negatives for molds, the fabrication of tools by the direct deposition of weld material, the

brazing of metallic laminations, and vapor and spray steel deposition over patterns. However, significant advances are required to achieve the desired surface finish, accuracy, and material properties.

7.8 Ductile-Regime Grinding

Ductile regime grinding is grinding with an extremely small local depth of cut, so that the predominant material-removal mechanism is plastic flow and not fracture⁶⁴. It enables the grinding of brittle materials with surface finishes similar to those achieved by polishing or lapping while permitting the fine tolerances and complex shapes achievable in the deterministic grinding process. Ductile-regime grinding requires a combination of high stiffness and sub-micrometer precision for the wheel infeed motion to control the local small depth of cut, and thus, enable ductility.

A disadvantage of ductile-regime grinding is the low material removal rate due to the small depth of cut. Therefore, it is important to determine the critical depth of cut below which the predominant material removal mechanism is plastic flow. The material removal rate can be improved by increasing the contact area between wheel and workpiece. In creep-feed grinding this is achieved by combining a large depth of cut with a small feed rate, resulting in a small local depth of cut at the individual grids. The large contact area, however, results in higher cutting forces and force variations which puts further demands on the rigidity of the workpiece, grinding wheel, and machine⁶⁵.

Of critical importance in this field is the optimization of the grinding process to achieve maximum removal rate, minimal residual damage, and lowest cost⁶⁶⁻⁶⁸. A large number of parameters need to be optimized (e.g., feed, depth of cut, wheel speed, table speed, machine tool characteristics, grinding fluid, wheel characteristics, and the trueing and dressing procedure). The machining rate and the surface integrity of the workpiece are very sensitive to the selection of these parameters for each specific material and application.

8. Conclusions

In the previous chapters, critical needs for leading-edge technology developments in machining and precision were discussed. These developments are important to the competitiveness and economic growth of the U.S. discrete part industry. In this section, the major trends in machining and the key technical challenges they pose for the discrete part industry and NIST are summarized. A listing of the research needs identified in the previous sections of the report are combined in Appendix B.

To summarize, traditional machining methods (e.g., turning, milling and grinding) have changed gradually over time. Most improvements have been evolutionary. However, with the advent of numerical controllers and CNC machines there has been an accelerated trend towards higher speed, increased automation, more complex part geometries, greater flexibility and greater precision. Advances in machine configurations, such as combination milling-turning, are enabling the machining of more complex geometries in one setup, thereby increasing throughput, agility and accuracy. The increased use of advanced materials such as

ceramics and composites is spurring the growth of emerging processes. The pace at which manufacturers need to introduce new products into the market is accelerating the search for higher flexibility. Flexibility and rapid changeover, through the use of modular tooling and fixturing, is becoming increasingly important. The increasing search for flexibility is also resulting in a shift from dedicated machinery to increased use of multi-purpose CNC machining centers. Increased *flexibility*, increased *precision*, increased *automation*, increased use of *advanced materials*, and the emergence of *new processes* are the key driving forces in manufacturing today.

To remain competitive in world markets, the discrete-part industry must produce innovative quality products at competitive costs in a timely manner. As evidenced by the success of Japan, improvements in, and control of, manufacturing precision are critical to meet market demands. How and how well product components can ultimately function or be assembled is, to a large extent, determined by the accuracy of the realized geometries. Tighter tolerances are required for interchangeability, automatic assembly, miniaturization, integration, design simplicity and improved performance and reliability.

Improvements in machining precision require better understanding of machining processes and machine accuracy, more accurate machine tools, and robust adaptive process control based on deterministic manufacturing principles, in-process, process-intermittent and post-process measurements. In fact, technology and manufacturing leaders see in-process measurement and control as the key technology for machining competitiveness⁷.

Both improvements in, and control of, manufacturing precision are dependent upon the availability of a robust, supportive infrastructure which includes well defined measurement and analysis methods, improved factory-hardened sensors, standards, reliable machining data, and databases on the cost of precision. The importance of metrology to discrete-part manufacturing cannot be underestimated. Accurate measurements are required for process control, to insure product quality and to improve manufacturing precision. Measurement standards and sensors are required to obtain the real-time data needed to monitor and control the precision of manufactured parts and manufacturing processes, to compensate errors, and to enable predictive maintenance. The importance of infrastructure to manufacturing is shown in Figure 9 where it can be seen that infrastructural tools are the foundation on which all manufacturing tasks rest.

While much progress has been achieved, machine tool characterization remains an expensive, time-consuming endeavor that is beyond the reach of small and medium size enterprises. Accordingly, few manufacturers are able to enjoy the full benefits to be derived from machine tool characterization. The development of fast, in-situ, practical machine tool characterization procedures should be given a high priority. Moreover, to insure that machine tool characterization leads to better precision in manufactured parts, attention should be given to the development of methods to translate machine performance parameters into machined part accuracy and precision.

Because of the large number of "older" machine tools in use today, the basic soundness of these machines, and the scarcity of funds for capital investments, it is important to develop methods for incorporating innovations into older machine tools.

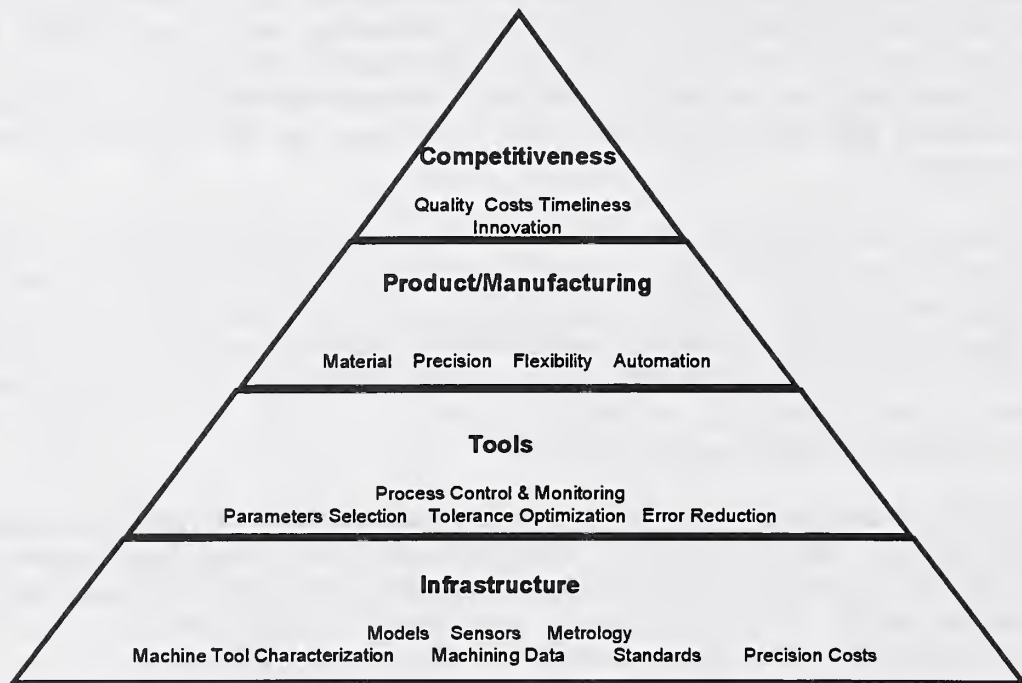


Figure 9. Importance of Infrastructure to Manufacturing Competitiveness.

In the area of standardization, special efforts should be made to harmonize the terminology, the measurements, and the analysis methods embodied in both national and international standards. In cooperation with industry, interface standards for controllers and sensors used in process measurement and control should be developed. Because of its third-party objectivity, NIST is in a unique position to provide the sustained and continuous leadership required. As was observed in an earlier chapter, variations in definitions and test procedures embodied in the standards of various nations can lead to substantial barriers to international trade.

Finally, the increased use of advanced materials, the increasing demand for flexibility, fast changeovers, higher precision, and greater throughput are resulting in the emergence of new processes, including high-speed machining, hard cutting, thermally assisted machining, dry machining, ultrasonic machining, ductile grinding, and material increment manufacturing. Each of these processes holds much promise for increasing the competitiveness of the U.S. discrete-part manufacturing industry. However, while some of these emerging processes have found a niche in manufacturing, some are still years away from competing seriously with the more traditional machining techniques. Nevertheless, emerging processes undoubtedly will become increasingly important. For this reason, it is important for NIST to start building up the infrastructural tools that will be required to support them in the future.

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Appendix A. List of Workshop Participants

As mentioned in the introduction of this report, the analyses contained in this report are based upon published data and the findings of a workshop on precision in machining held on October 12, 1994 in Gaithersburg, MD. The workshop was sponsored by the Automated Production Technology Division of the Manufacturing Engineering Laboratory of the National Institute of Standards and Technology. Representatives from industry, the national laboratories and academia participated. A listing of the participants and their organizations is given below.

D. Blomquist	National Institute of Standards and Technology
D. Carter	Lawrence Livermore National Laboratory
M. Davies	National Institute of Standards and Technology
A. Donmez	National Institute of Standards and Technology
J. Drescher	Pratt & Whitney
C. Evans	National Institute of Standards and Technology
J. Flinchbaugh	Weldon Machine Tool
G. Garitson	Cummins Engine
D. Godfrey	Manufacturing Resources
J. Halley	McDonnell Douglas Aerospace
K. Harper	National Institute of Standards and Technology
T. Hinnerichs	Sandia National Laboratory
R. Hocken	University of North Carolina at Charlotte
R. Hodge	Cincinnati Milacron
M. Ignagni	Honeywell
R. Jackson	National Institute of Standards and Technology
Y. Matsumoto	Timken
R. McClure	Moore Special Tool
W. Pflager	Landis
B. Podlesnik	Allied Nut & Bolt
J. Redmond	Sandia National Laboratory
C. Rodriguez	Ohio State University
C. Shen	General Motors
H. Soons	National Institute of Standards and Technology
R. Wells	National Institute of Standards and Technology
J. Westmoreland	National Center for Manufacturing Sciences
T. Williams	Martin Marietta Energy Systems
S. Yaniv	National Institute of Standards and Technology
S. Young	Honeywell
M. Wozny	National Institute of Standards and Technology

Appendix B. Key Metrological and Technological Challenges

The technical issues resulting from the on-going trends in machining are discussed in the main body of this report. In this appendix, the key research needs[†] in machining precision identified in the various sections of the report are combined. These research needs are based upon analyses of published data and the findings of the workshop on precision in machining. Research needs in hard turning and other emerging processes are not considered here, as they will be the object of a separate workshop and report.

During the course of the workshop on precision machining some general findings were emphasized by the participants. These include the need:

1. For NIST to provide consistent and sustained standardization support and participation in national and international standards to insure harmonization of terminology, measurement methods and analyses. Workshop participants emphasized the need for sustained management commitment and support to enable participation by the right technical people.
2. To develop mechanisms for technology transfer, and to realize traceability and accreditation of machine tool characterization services.
3. To assess "real" trends in machining precision rather than "perceived" trends. These "real" trends should be determined from studies conducted in many industrial settings. Determination of "real" trends is important for planning future manufacturing equipment.
4. To assess benefits to be derived from precision in manufacturing. These analyses should take into account the total manufacturing enterprise and be based upon real cases from a wide variety of manufacturing sectors.
5. To assess the cost-benefits of machine tool characterization, error compensation, and closed-loop precision manufacturing. These studies should include assessment of the state of the art and limitations in real production environments and address various classes of machines.
6. To assess the impact, challenges, and opportunities of environmental and safety concerns on machining practices.

B.1 Machine Tool Characterization

Most experts agree that, while much progress has occurred in the field of machine tool characterization, characterization remains an expensive, time-consuming endeavor that is beyond the reach of small- and medium-sized enterprises. Key metrological and technical challenges in this area are listed below.

[†] Research requirements are identified irrespective of the organization where the research is to be carried out.

1. Development of fast, in-situ, practical machine tool characterization procedures. These procedures, and the related data analysis, should be user-friendly, should lead to a significant decrease in the time and equipment required to characterize machine tools, and yield meaningful accuracy parameters.
2. Identification of key environmental factors and process variables that affect machine tool accuracy.
3. Determination of short but comprehensive duty cycles that show the effects on machine tool accuracy of the parameters identified in 2 above.
4. Determinations of how often and what kind of machine tool evaluations are required for a variety of machines and production environments.
5. Development of methods to translate machine tool performance parameters into machined part errors.
6. Development of methods to translate design tolerances into required machine tool performance parameters.
7. Development of the data needed to insure that machine tool characterization standards are based upon the state of the art.
8. Identification of the machine tool features required to facilitate performance evaluation.
9. Expansion of current research on machine tool characterization to include a larger variety of machines, and dynamic conditions.
10. Incorporation of the cutting process into the machine tool characterization method.
11. Development of error budget procedures for machine tools and machined parts.
12. Development of diagnostic measurement methods to enable predictive maintenance, including development of appropriate sensors.

B.2 Machine Tool Performance Enhancement

Error compensation can be a reliable, agile, and cost-effective method to improve the accuracy of machine tools. However, its application suffers from the many problems of machine tool performance evaluation. Key technical challenges in this area are given below.

1. Research on precalibrated error compensation should be continued. More attention should be given to error avoidance techniques and active error compensation. Special emphasis should be placed on developing methods to suppress vibrations.
2. Error compensation research should be performed on a larger variety of machines.

3. Develop more reliable techniques to incorporate into error compensation the wide variety of environmental conditions encountered in industrial settings.
4. Continue research on machine tool retrofit, including the development of open-architecture controllers.
5. Document the complete error compensation procedure used on various machine types in real production environments. Documentation should include all steps (e.g., error assessment, error modeling, used sensors, implementation in controller, problem areas and evaluation of results, including cost).
6. Develop the data required for the development of procedures that enable the generalization of error models across different machine tools of the same type in different environments.
7. Develop procedures for machine tool design, manufacturing and maintenance that take into account the benefits and limitations of error compensation.
8. Identify key machine tool design features and manufacturing procedures that reduce performance variations across machines of the same type.

B.3 Closed-Loop Precision Manufacturing

Machine based quality control exploits the concept of deterministic manufacturing. It is based on the premise that most errors in the manufacturing process are repeatable and predictable. Therefore, errors can be predicted and compensated. Thus, the quality of "arbitrary" products can be assured by controlling both the manufacturing process and the equipment used. This is achieved by statistical process control methods, in-process measurements and control, error compensation, process intermittent and post-process inspection. Key technical challenges in this area are listed below.

1. Identification of key machine performance indicators that correlate best with the precision of the machined parts (e.g., acoustic emission, vibration, force, temperature, etc.).
2. Development of reliable, non-intrusive, factory-hardened sensors.
3. Development of sensors and measurement procedures to determinate the precision of the machined parts in-process and independently of the machine precision.
4. Development of sensors to detect tool wear and procedures for real-time compensation.
5. Development, in cooperation with industry, of sensor and controller interface standards.
6. Development of methods to shutdown machine tools when prescribed limits of indicators described in 1 above are exceeded, and to present diagnostic information.

7. Development of the architecture required to process feedback data to update error models, and to implement these into controllers.
8. Testing of closed-loop precision manufacturing concepts across a variety of machines types and industrial settings.

B.4 Process Modeling

Process modeling is an attempt to describe in mathematical terms the interactions that occur between the tool and the workpiece during cutting. Process models are used to predict and optimize cutting performance, with a minimum of or without application oriented cutting tests. Key technical challenges in this area are listed below.

1. Development of procedures for increasing accessibility of state of the art process models, machinability data, and process optimization techniques.
2. Development of the basic knowledge, databases, and models required to describe the complex interactions between machining characteristics, tools, workpiece material, and process parameters needed for cost-effective machining of advanced materials.
3. Investigation of the applicability of modern analysis techniques such as nonlinear dynamics, neural networks, expert systems and molecular dynamics.
4. Development of sensors to monitor and optimize the machining of advanced materials. Special attention should be given to monitoring surface integrity.
5. Determination of machining on residual stresses and their effects.
6. Development of measurement techniques to assess quickly the machine/tool/workpiece dynamic properties required to select stable process parameters.
7. Development of sensors, actuators, process optimization schemes, and adaptation of modern signal-processing techniques to monitor the process and reduce chatter.
8. Development of improved wear models and reliable, non-intrusive, and robust tool wear monitoring and compensation systems.
9. Development of tougher, more refractory tool materials and coatings, especially for high-speed machining and the machining of advanced materials.

B.5 High-Speed Machining

There exist several technical challenges in the application of high-speed machining. These include the development of:

1. Tool materials that last for a sustained time at high cutting speeds.

2. High-power and high-speed reliable spindles (e.g., air, magnetic, or hybrid angular ball bearings). Attention should be given to lubrication, heat generation, centrifugal forces, and dynamic aspects in the development of these spindles.
3. Fast feed drives and suitable guideways to achieve the required high accelerations and speeds (e.g., linear motors and multiple thread roller drives).
4. Machine tools with a minimum number of moving parts and lightweight, high stiffness, structures to achieve high accelerations (e.g., composites, thin walled steel, titanium, and aluminum).
5. Controllers that allow fast cornering and are able to handle large amounts of CNC code in a timely manner⁵⁴.
6. Schemes to reduce the required amounts of CNC code⁵².
7. Alternative tool holder interfaces designed for high stiffness and axial positioning accuracy at high speeds⁵². Recently a new interface was introduced in a Standard^{55,56} that is the object of some controversy as it is likely to lead to complex designs and incompatibility with current tools and spindles⁵⁷.
8. Active and passive devices to ensure the safety of the operator and the machine.
9. Efficient chip removal techniques.

B.6 Costs and Benefits of Precision

1. Develop the data required to establish the relationship between precision and costs in different manufacturing environments, for a variety of parts and machining processes.
2. Develop procedures for optimization of part tolerances and machine specifications based upon data obtained in 1 above.
3. Develop transfer mechanisms to enable small and medium manufacturing enterprises to choose the most cost-effective strategy to achieve a given level of precision.

